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# INDEX TO BENET LABORATORIES TECHNICAL REPORTS – 1999

R. D. NEIFELD

JULY 2000

US ARMY ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER
CLOSE COMBAT ARMAMENTS CENTER
BENÉT LABORATORIES
WATERVLIET, N.Y. 12189-4050

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February 1999 Final

DYNAMIC ANALYSIS OF A 155-MM CANNON BREECH

Contract No. GS-35F-5296H

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ARCCB-CR-99001

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Stephan VanDyke-Restifo – Benet Laboratories Project Engineer. Presented at the 9th U.S. Army Gun Dynamics Symposium, McLean, VA, 17-19 November 1998. Published in proceedings of the symposium.

Approved for public release; distribution unlimited.

This report describes a finite element analysis of the breech closure for the 155-mm M199 cannon, which is normally mounted on the towed howitzer M198. This configuration has an excellent record for reliability in the field and is easy to service. However, when the breech is used in an ammunition test environment, some maintenance problems exist. Our analysis was for a nine-body problem with thirteen contact surfaces, and was solved for both static and dynamic load cases. The two dynamic loads were of similar shape with different loading times. The nine bodies in the model included a facility mount, four major structural components, the obturator seal, and three minor components. The results showed that the major components are normally subjected to quasi-static loading, but under fast "pressure spike" loading, the dynamic effect can be important. This is particularly true for the contact between minor components that can show extreme behavior with the fast-loading rates.

Cannon, Breech, Dynamics, Vibrations, Finite Element

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THE USE OF THERMAL ANALYSIS IN THE CHARACTERIZATION OF A POLYMER SURFACE

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PRON No. PJ8K2D1DEX

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ARCCB-TR-99002

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Fuel cells are electrochemical systems that convert hydrogen into electricity without combustion. A proton exchange membrane (PEM) fuel cell power system consists of a polymer membrane, finely disbursed catalyst, and a gas humidifying system. Thermogravimetry (TGA) and differential scanning calorimetry (DSC) are powerful tools that can be used to characterize the physical properties of a polymer membrane. Ion chromatography can monitor the presence of contaminating ions in the aqueous condensate. TGA can easily measure the distribution of metal catalysts on a polymer surface due to the much lower decomposition temperature of the polymer. DSC can be used to measure the concentration of Teflon in a polymer blend by measuring the melting energy.

Fuel Cell, Nafion, Thermal Analysis,
Catalyst, Ion Chromatography

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VISUALIZATION OF CANNON WEAR USING ULTRASONIC MEASUREMENTS AND MATLAB®

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CUGS (Computerized Ultrasonic Gauging System), the synergistic use of ultrasonic and computer technology, is used to obtain measurements of a gun tube's bore surface. The bore surface is displayed as a "topographical map" whose colors are related to the physical dimensions of lands and grooves. In this manner, bore wear and erosion can be detected as differences in colors. Visualization software is written in the MATLAB® programming language/environment. All aspects of the process are described with special emphasis on the visualization algorithms and techniques. Also described are examples of typical results obtained from CUGS and the visualization software.

Ultrasonic Gauging, Wear and Erosion, Scientific Visualization, Centering Algorithm, Newton Iteration

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LASER-ULTRASONIC CHARACTERIZATION OF
ELECTRODEPOSITED CHROMIUM COATINGS

AMCMS No. 6111.01.91A1.1

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ARCCB-TR-99004

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Chromium coatings were electrodeposited onto steel substrates, under controlled conditions. A pulsed laser generated ultrasonic waves in the specimen, and a Michelson interferometer detected the ultrasonic waves at the surface. Signal processing techniques were used to obtain the surface wave velocities, and the various modes are discussed. Conventional piezoelectric techniques were also used for generation and detection of bulk wave velocities to correlate with the surface wave results. A difference technique was used to obtain the bulk measurements: time transit and thickness were measured before and after chromium plating and the velocities evaluated from the respective differences of the data thus obtained.

Ultrasonics, Laser-Ultrasonics, Elastic Properties, Coatings 12

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A PROFRESS REPORT ON X-RAY DIFFRACTION MEASUREMENTS ON NEW LOW-THERMAL CONDUCTIVITY THERMOELECTRIC MATERIALS

AMCMS No. 6111.01.91A1.1

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ARCCB-TR-99005

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Thermoelectric devices and materials have potential applications in refrigeration and power generation. An X-ray diffraction study was made documenting the phase and the lattice parameter of both some new thermoelectric compounds and some previously known compositions. The materials contained primarily Ir, Rh, Sb, Sn, and Pt. Improvements in the measurement procedures resulted in improved accuracy in lattice parameter measurements and in peak intensity measurements.

Thermoelectric Materials, Ir, Rh, Sb, Sn, Pt,
Skutterud, Lattice Parameters

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COMPUTERIZED ULTRASONIC GAUGING

AMCMS No. 6111.01.91A1.1

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Submitted to *Research in Nondestructive Evaluation*, A Journal of the American Society for Nondestructive Testing.
*Current Address: Textron Systems Division, 201 Lowell Street, Wilmington, MA 01887.

Approved for public release; distribution unlimited.

A high-precision ultrasonic gauging system has been designed and implemented for use on a CNC lathe. The system uses a PC along with a number of plug-in cards to generate, receive, and process ultrasonic signals. The system has been reliably used both during and after machining operations. It is capable of simultaneous measurement of wall thickness, runout, outer diameter radius, inner diameter radius, and concentricity of the inner diameter and outer diameter. Data densities of 2000 measurements per revolution of all parameters can be achieved. Data can be acquired at lathe spindle speeds that keep the outside part surface moving at less than about 2000 surface feet per minute. A real-time, pseudo-color, image of the wall thickness is provided during operation. The system can receive setup and operational instructions from the lathe CNC so that operation can be accomplished with very little operator involvement.

Ultrasonics, Gauging, Thickness Measurements,
Wall Thickness, Gun Tubes

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THIN-FILM DENSITY DETERMINATION OF TANTALUM, TANTALUM OXIDES, AND XEROGELS BY MULTIPLE RADIATION ENERGY DISPERSIVE X-RAY REFLECTIVITY

AMCMS No. 6111.01.91A1.1

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X-ray reflectivity provides a nondestructive technique for measuring density in thin films. A conventional laboratory, Bragg-Brentano geometry diffractometer was employed to show the generalized feasibility of this technique. X-ray tubes with chromium, copper, and molybdenum targets were used to provide a large overlap of energies for density fitting. X-ray tube alignment and sample alignment were explored to find a self-consistent measurement technique. The real and complex indices for tantalum, $TaO_x$, and porous $SiO_2$, also known as "xerogel," were calculated and used in a reflectivity-fitting routine. The density results from multiple energies provided a self-checking method for true density extrapolation from misaligned samples. Density results for the xerogel films were compared with measurements by Rutherford backscattering spectrometry and by optical ellipsometry, and showed consistency within errors.

X-Ray Reflectivity, Density, Tantalum, Tantalum Oxides, Energy Dispersive

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BAUSCHINGER EFFECT DESIGN PROCEDURES FOR AUTOFRETTAGED TUBES INCLUDING MATERIAL REMOVAL AND SACHS' METHOD

AMCMS No. 6226.24.H181.0

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Autofrettage is used to introduce advantageous residual stresses into pressure vessels and to enhance their fatigue lifetimes. The Bauschinger effect serves to reduce the yield strength in compression as a result of prior tensile plastic overload and can produce lower compressive residual hoop stresses near the bore than are predicted by 'ideal' autofrettage solutions (elastic/perfectly plastic without Bauschinger effect). A complete analysis procedure is presented which encompasses representation of elastic-plastic uniaxial loading material behavior and of reverse-loading material behavior as a function of plastic strain during loading. Such data are then combined with some yield criterion to accurately predict elastic-plastic residual stress fields within an autofrettaged thick cylinder. Pressure for subsequent re-yielding of the tube is calculated. The numerical procedure is further used to determine residual stress fields after removal of material from inside diameter (ID) and/or outside diameter (OD), including the effects of any further plasticity. A specific material removal sequence is recommended. It is shown that Sachs' experimental method, which involves removing material from the ID, may very significantly overestimate autofrettage residual stresses near the bore. Stress ranges and stress intensity factors for cracks within such stress fields are calculated together with the associated fatigue lifetimes as such cracks propagate under cyclic pressurization. The loss of fatigue lifetime resulting from the Bauschinger effect is shown to be extremely significant.

Bauschinger Effect, Autofrettage, Gun Tubes, Sachs' Method, Residual Stresses, Fatigue Life, Pressure Vessels

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ANALYSIS OF A PISTON EXPERIENCING ENVIRONMENTALLY-ASSISTED CRACKING AS A RESULT OF COMPRESSIVE OVERLOADING

AMCMS No. 4221.23.0000.0

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A piston used in service in a closed-ended pressure vessel, as a component of the seal for the vessel, cracked after as few as two high-pressure loading cycles. As a further complication, the finite element analysis was predicting compression on the cracked piston face during the loading cycle. The cracks in the piston emanated in a radial fashion and were measured at 1.5-mm deep. Upon subsequent loading, the cracks grew in length (in large incremental advances), but did not propagate any deeper than the initial 1.5-mm. In all instances the robust design did not leak. A closer look at the finite element analysis revealed that the piston, made from Maraging 200 steel, was loaded in compression to above the compressive yield point of the material. The initial loading set up a residual tensile stress as a result of the compressive yielding. On the next successive loading, this tensile residual stress field, coupled with the hydrogen-rich products in the pressure vessel and a highly susceptible material, resulted in cracking. The fact that the cracks were only 1.5-mm deep suggests that this was the extent of the compressive yielding, and that the cracks arrested themselves once the neutral axis or zero stress was encountered. The fracture morphology of the cracks revealed that they were intergranular in nature, and likely to be the result of hydrogen-induced cracking. At this point in the program the design of the piston was firmly established, so the only alternatives were to prevent the hydrogen from getting to the susceptible material, or to change to a less susceptible material. Consideration of the second alternative revealed no material that possessed the unique combinations of strength, toughness, hydrogen resistance, or producibility that were required. Therefore, plating of the piston with various nickel and chromium combinations was investigated. Laboratory tests were devised using a modified bolt-loaded compact specimen for conducting plating studies. The specimens were loaded near the yield strength of the material and exposed to a hydrogen-rich environment. After over 300 hours of exposure, no cracking had occurred in any of the electroplated nickel specimens. These results were then applied to the piston and placed into service. The piston currently has over 700 high-pressure loading cycles with no cracks observed.

Environmentally-Assisted Cracking, Hydrogen, Pressure Vessels
Compressive Overload, Nickel Coating

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LIQUID METAL EMBRITTLEMENT OF ASTM A723 GUN STEEL BY INDIUM AND GALLIUM

AMCMS No. 8Y10.00.0000.0

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ARCCB-TR-99011

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An investigation was performed to determine the effects of gallium and indium on the liquid metal embrittlement of ASTM A723 gun steel. Liquid metal embrittlement tests were conducted slightly above the melting temperature of the embrittling metal in an elevated temperature furnace coupled to an Instron mechanical tester. Low cycle fatigue and monotonic tensile testing of notched tensile specimens were performed. In addition, the effect of strain rate on the embrittlement of ASTM A723 by gallium was evaluated. The low cycle fatigue tests showed a high sensitivity to liquid metal embrittlement; both the gallium and the indium significantly degraded the fatigue life of the gun steel. Monotonic tests on ASTM A723 also showed an embrittling effect with both gallium and indium, although the effect was less severe than when tested in low cycle fatigue.

Liquid Metal Embrittlement, Environmental Cracking, Gallium Indium, Gun Steel, High-Strength Steels, ASTM A723

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ANALYSIS OF ENGRAVING AND WEAR
IN A PROJECTILE ROTATING BAND

AMCMS No. 6226.24.H191.1

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A large deformation analysis of the engraving process and wear in a projectile rotating band is considered by using the finite element program ABAQUS. The tube and the projectile are assumed to be rigid, and the bore of the tube is assumed to be smooth and axisymmetric. An elastic-plastic material model is chosen for the copper band, which remains attached to the projectile, and an appropriate coefficient of sliding friction is chosen. The magnitude and distribution of the contact pressure between the band and the tube are obtained during engraving. The band pressure is large with severe plastic deformation occurring in the band.

Engraving, Wear, Projectile, Rotating Band, Plastic Deformation 16

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THERMAL DAMAGE AND SHEAR FAILURE OF CHROMIUM PLATED COATING ON AN A723 STEEL CANNON TUBE

PRON No. F18X2011M21A

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Degradation of the electroplated chromium coating at the bore of A723 steel cannon barrels is characterized here following cannon firing and used to model the coating failure process. Transient thermal stresses due to firing are calculated using one-dimensional heat flow analysis and used as input to a shear failure model of the coating/substrate couple. The cracking array that develops in the coating and substrate with repeated thermal cycles, the configuration of cracked segments of the coating, and the elevated temperature properties of the coating and substrate are considered in the shear failure model. Accordingly, the coating failure behavior predicted from the model is compared with the observations of coating failure mechanisms from actual fired cannon tubes. The results of the investigation show that growth of hydrogen cracks in the steel under the chromium coating allows broadening of cracks in the coating, and subsequent shear failure of the steel under a segment of coating due to transient thermal stresses. Loss of coating segments then leads to rapid hot gas erosion of the steel and loss of function of the cannon tube. The objective is to model the final critical phase of thermal damage imparted to a chromium coating on a cannon bore that leads to the separation of a segment of coating.

Thermal Damage, Chromium Plating, Alloy Steel, Cannon Tube, Hydrogen Cracks, Thermal Stress, Residual Stress

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THERMOMECHANICAL MODEL OF HYDROGEN CRACKING AT HEAT-AFFECTED CANNON BORE SURFACES

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Two examples of hydrogen cracking in the heat-affected region of fired cannons are given, including metallographic evidence of damage at various depths near the bore surface. The depth of steel transformation due to firing is used to verify near-bore temperature distributions and transient and residual stress distributions calculated using classic one-dimensional heat flow analysis. Predicted depths of thermal damage and hydrogen cracks compare well with observed depths for different crack orientations and firing temperatures. Laboratory fracture mechanics tests using bolt-load compact specimens are described, including crack growth and blunt-notched tests in acid-hydrogen environments. The utility of the thermal and fracture mechanics analyses and the laboratory fracture mechanics tests used with cannons are discussed for weld applications.

Thermomechanical Model, Cannon Bore, Thermal Stress, Hydrogen Cracking, Fracture Mechanics

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March 2000 Final

PROCEEDINGS OF THE NINTH U.S. ARMY SYMPOSIUM ON GUN DYNAMICS

AMCMS No. 6226.24.H191.1

Eric L. Kathe, Editor

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Note the report number was assigned in advance of report publication. The final copy of this publication was approved in March 2000.

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This publication represents a compilation of the technical papers concerning modeling, analyses, design, measurements, and instrumentation of gun dynamics. The authors represent a cross section of the scientific and technical community, including universities, industrial, and government research laboratories.

Ballistics, Barrel Vibration, Dynamics, Precision, Controls, Target Acquisition, Accuracy, Heating, Erosion

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Final

GRAY LAYERS AND THE EROSION OF
CHROMIUM PLATED GUN BORE SURFACES

AMCMS No. 6226.24.H191.1

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The present report describes observations and analyses in a survey study of erosion damage in chromium plated gun bore surfaces. Sections of three fired chromium plated 120-mm M256 gun tubes and two 155-mm gun tubes (M199 and XM297) were examined by optical microscopy, laser scanning confocal microscopy (LSCM), and electron microprobe analyses. These tubes experienced significant erosion damage and chromium loss. A rifled portion of the 155-mm M199 tube was plated with low contractile (LC) chromium and the 155-mm XM297 and 120-mm M256 tubes were plated with high contractile (HC) chromium.

New insights regarding the erosion process and the origin of chromium loss are obtained by investigation of the initial damage to the steel at the tips of the fine cracks in the chromium. Reaction products from gas-metal interactions at the gun bore surface are normally difficult to find because of gas wash effects. Examination of unetched specimens from a variety of fired tubes shows that these products remain in place in the relatively protected regions beneath the chromium when chromium crack widths are small. The initial damage is manifested as gray layers or gray regions in the steel at the tips of the fine chromium cracks. Electron microprobe analyses indicate that these gray layers are composed of iron sulfide, iron oxide, or mixtures of the two compounds.

Erosion, High Contractile Chromium, Low Contractile Chromium,
Iron Sulfide, Iron Oxide, Chromium Spallation, White Layers

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ANALYSIS OF MOLTEN SALT AND SPUTTER-DEPOSITED COATINGS ON STEEL CYLINDERS

AMCMS No. 6111.01.91A1.1

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Presented at the 26th International Conference on Metallurgical Coatings and Thin Films, San Diego, CA, 12-16 April 1999.
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Prototype tantalum coatings, electrochemically deposited from a molten salt onto 20-mm interior bore steel liners, exhibited superior wear and erosion behavior compared to chromium coatings. The liners were subjected to cyclic exposures of high temperature, pressure, and an aggressive chemical environment. X-ray analysis of the coatings revealed a low-hardness, randomly-oriented, body-centered-cubic, α-phase tantalum. Formation of tantalum oxides (predominantly $Ta_2O_5$), swaging due to the low-hardness of the coatings, a 2-μm layer consisting of tantalum and carbon at the tantalum/steel interface, and surface compressive residual stresses were observed. Cylindrical magnetron sputtering systems were constructed to coat 45-mm interior bore steel cylinders to protect them from wear and erosion. X-ray diffraction, scanning electron microscopy, photomicrography, and hardness analysis of several sputter-deposited tantalum specimens revealed coatings consisting of soft body-centered-cubic α-phase and hard tetragonal β-phase tantalum.

Molten Salt Deposition, Cylindrical Magnetron Sputtering Deposition, Tantalum, Thick Refractory Coatings 23

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October 1999 Final

LOADING FREQUENCY AND ITS EFFECTS
ON THE FATIGUE LIFE OF A723 STEEL

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The fatigue life of pressure vessels manufactured from two strength levels (166 Ksi and 190 Ksi) of A723 steel has been modeled, and the life predictions using the model have verified that a field loading cycle is equivalent to a laboratory pressurization loading cycle. One key assumption in the model is that a minimum crack initiator must be present in order to attain a one-to-one correlation. If the minimum crack initiator is not present, there will be a large error between laboratory and field loading when predicting final fatigue failure. This study shows that a crack initiator greater that about 0.019 inch (for 166 Ksi yield strength steel) and 0.008 inch (for 190 Ksi yield strength steel) will result in the one-to-one correlation that is sought. No attempt has been made to model environmental effects that can greatly affect the results presented here.

Frequency, Fatigue Life, Life Prediction, Crack Initiation

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FATIGUE LIFE ASSESSMENT OF
155-MM M776 CANNON TUBES

AMCMS No. 6226.24.H191.1

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Benet Laboratories has the responsibility for safe fatigue life (durability) testing of cannon system components. This safe fatigue or service life evaluation is accomplished by conducting constant amplitude fatigue testing in a laboratory setting. One such cannon component that requires testing is the gun tube. After each tube has received the required number of live fire rounds necessary to generate initial cracking at the bore surface (also known as heat-check cracking), it is brought to the laboratory for final hydraulic fatigue testing.

A sample size of two 155-mm M776 gun tubes was hydraulically fatigue tested to failure at Benet Laboratories to assist in determining the safe fatigue life for the weapon. This report contains the results of the fatigue tests conducted on the subject tubes, including material inspections, failure lives, and the resulting value for safe fatigue life of the XM776 gun tube.

XM776 Cannon, Final Safe Fatigue Life, Fatigue Testing, Extreme Service
Condition Pressure, Ultrasonic Inspection, Statistical Analysis

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November 1999 Final

X-RAY DIFFRACTION TECHNIQUES AND FINITE ELEMENT MODELING TO CONTROL RESIDUAL STRESS IN HIGH-TEMPERATURE PRESSURE VESSELS

AMCMS No. 6111.01.91A1.1

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Manufacturing operations, such as swage autofrettage, shot peening, and overload processes, have been used to impart advantageous residual stresses to improve fatigue life in components used in high-temperature pressure vessels. Both experimental and modeling techniques depend on the geometry and processing history of the component under investigation. This report compares x-ray diffraction residual stress measurements in a swage autofrettaged steel cylinder with finite element modeling results of a cylinder with a given bore expansion. The report also examines an analytical model of a cylinder under internal pressure, including both Bauschinger and strain-hardening effects. From a simple swaged cylinder to a complicated perforated cylinder and overstrained and shot-peened multiple-lug breech structure, control of residual stresses through experimental and modeling efforts is vital in the design of pressure vessels. This report discusses the role of slicing operations, surface polishing, surface roughness, and resolution effects in structures that contain high stress gradients.

Pressure Vessels, Residual Stress, Surface Roughness Effect,
Surface Polishing Effect, Surface Stress Gradients, Slicing Effect

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COATING EVALUATION USING ANALYTICAL AND EXPERIMENTAL DISPERSION CURVES

PRON No. 8LRMFARD77

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Well-bonded or "welded" contact and poorly bonded or "smooth" contact bonds were studied. As examples of welded contact bonds, we used sputtered tantalum and electrodeposited high contraction chromium coatings that were deposited onto steel substrates under controlled conditions. In order to simulate smooth contact coatings, thin sheets of nickel and tantalum were epoxied to copper and steel substrates, respectively. We used the method originated by Cielo et al. to gather data consisting of laser generation of the surface waves in an annular ring and laser detection in the center. Wavelet techniques were used on the surface wave-detected signals in order to obtain the experimental dispersion (velocity-frequency) curves. The experimental dispersion curves were compared to theoretical curves to give insight into the bond quality. It was found that the experimental results correlated well with the theory for the welded case.

Coatings, Dispersion Curves, Welded Contact Bonds, Smooth Contact Bonds, Wavelet Techniques, Tantalum, Chromium

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